

INTERPRETATION OF FERROAN ANORTHOSITE AGES AND IMPLICATIONS FOR THE LUNAR MAGMA OCEAN. C. R. Neal¹, D. S. Draper². ¹Dept. Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (neal.1@nd.edu). ²ARES, NASA Johnson Space Center, 2101 NASA Parkway, Houston TX 77058, USA (david.draper@nasa.gov).

Introduction: Ferroan Anorthosites (FANs) are considered to have purportedly crystallized directly from the lunar magma ocean (LMO; e.g., [1]) as a flotation crust. LMO modeling suggests that such anorthosites started to form only after >70% of the LMO had crystallized [2-7]. Recent age dates for FANs have questioned this hypothesis as they span too large of an age range (e.g., [8-10]). This means a younger age for the Moon-forming giant impact or the LMO hypothesis is flawed. However, FANs are notoriously difficult to age date using the isochron method. We have proposed a mechanism for testing the LMO hypothesis through using plagioclase trace element abundances to calculate equilibrium liquids and compare them with LMO crystallization models [11]. We now examine the petrography of the samples that have Sm-Nd age dates (Rb-Sr isotopic systematics may have been disturbed [12]) and propose a relative way to age date FANs.

FAN Sm-Nd Ages

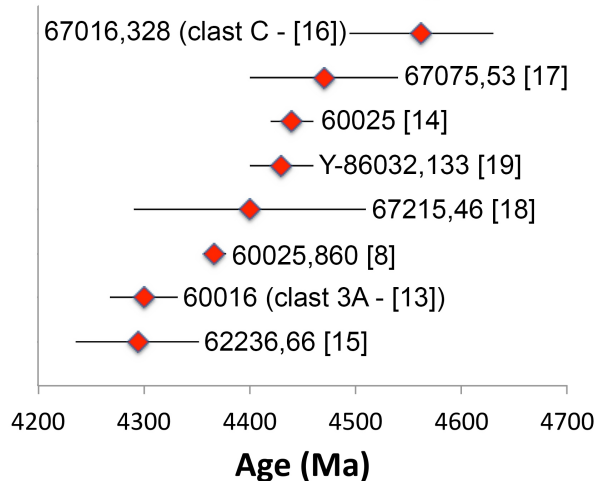


Figure 1: FAN Sm-Nd ages span 268 million years.

Sm-Nd Ages of Ferroan Anorthosites: Seven FANs have been age dated by the Sm-Nd method (Fig. 1): 60016 (clast 3A – [13]); 60025 has two distinct Sm-Nd ages [8,14]; 62236 [15]; 67016 (clast C – [16]); 67075 [17]; 67215 [18]; and Y-86032,28 (clast LG – [19]). Ages range from 4.562-4.294 Ga, which is 268 m.y. (excluding uncertainties). If all FANs came from the LMO, at least the last quarter to third of the LMO took this long to crystallize. It has been hypothesized that tidal heating and an insulating crust could have prolonged LMO crystallization [4]. Confounding the situation is the fact that the Mg-Suite of highlands samples, which had been considered to be intrusions

into the primary FAN crust [20], have ages that overlap with the FANs [8,21]. However, if all FANs crystallized from the LMO, they should lie along the LMO evolution path, and initial studies suggest they do [11]. However, literature data used in the study of [11] were generally from samples that had not been age dated. Using the age range shown in Figure 1, relative age dating can be carried out for those samples for which it is difficult/impossible to get reliable crystallization ages. It is assumed that all ages are crystallization ages.

Petrography: We get back to basics and look at the petrography of the samples for which ages have been determined (Fig. 1).

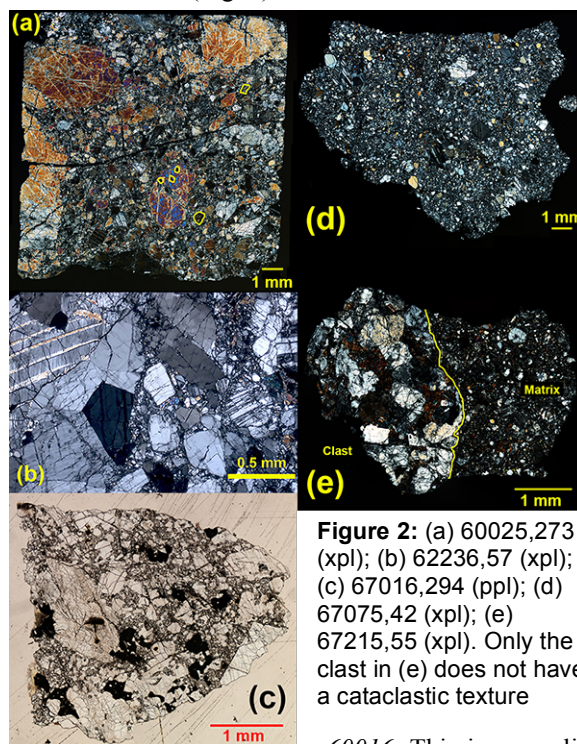


Figure 2: (a) 60025,273 (xpl); (b) 62236,57 (xpl); (c) 67016,294 (ppl); (d) 67075,42 (xpl); (e) 67215,55 (xpl). Only the clast in (e) does not have a cataclastic texture

60016. This is a regolith breccia containing clast 3A described by [22] from thin section ,229. It is not highly cataclasized and the coarse-grained plutonic texture is preserved.

60025. This is a cataclastic FAN that is “*probably a mixture of several FAN lithologies*” [23]. 60025,273 (Fig. 2a) is a thick section depicting the cataclastic texture, preservation of large plagioclase crystals, and minor pyroxene (outlined in yellow).

62236. A highly brecciated noritic FAN that lacks foreign lithic fragments [15]. Thin section ,57 shows a cataclastic texture with preservation of large (>1 mm) plagioclase and small pyroxenes (≤0.1 mm) (Fig. 2b).

67016. The age reported by [16] is for noritic FAN clast ,328 (clast C), which was taken from subsample ,6. We have examined thin section ,294 that was also taken from ,6, but it is not clear that the section is from the clast that was age dated. The noritic FAN is dominated by plagioclase (up to 2mm) with a significant proportion of pyroxene (up to 0.3 mm) and opaques (up to 0.5 mm) (Fig. 2c).

67075. This is a crushed FAN that was assembled from genetically-related fragments of a layered plutonic anorthosite (e.g., [24]). It has plagioclase (≤ 1 mm) with minor olivine, low-Ca pyroxene, high-Ca pyroxene and traces of Cr-spinel, ilmenite, Fe-Ni metal, troilite and silica. The subsample age dated was from parent ,4. Three of our thin sections (,42 ,48 ,50) were from parent ,14, with ,108 from parent ,1.

67215. The analyzed clast [18] was ,46 with corresponding thin section ,55 (Fig. 2e). It has an unbrecciated igneous texture dominated by plagioclase. Subordinate pyroxenes exhibit exsolution lamellae.

Y-86032. See [25] for details.

Relative Chronometry: FAN samples that have been age dated have all had their original texture modified by subsequent impact processes. Only the clast in 67215,55 appears to have escaped cataclasis, but the Sm-Nd age has large uncertainties (4.40 ± 0.11 Ga). 60025 has produced two distinct ages (4.44 ± 0.02 Ga [14]; 4.367 ± 0.011 Ga [8]), but this may be a result of two distinct FAN lithologies being age dated [23]. Assuming the ages represent crystallization from the LMO, the older samples should plot closer to the origin in Fig. 3, where the LMO evolution is plotted for the interval where FANs would have crystallized. This chemical trend is age calibrated using FAN ages (Fig. 1). Modeling [11] can be used to define an approximate age for FANs by plotting plagioclase equilibrium liquids on the age-calibrated LMO evolution trend (Fig. 3). Using data from [26,27], 60025 plots close to the older end of the range, whereas 67215 data plot around the younger end of the age range (Fig. 3). Relative ages can be calculated using the equilibrium liquid La and Nd data. Averaging these calculated ages using La and Nd yields 4.502 ± 0.022 Ga for 60025, and 4.238 ± 0.139 Ga for 67215. The 60025 age is similar to that reported by [14] although it is slightly older. The age for 67215 is younger than the Sm-Nd age (4.40 ± 0.11 Ga [18]), but because both ages have large uncertainties, they are within error. 67215 data do not plot on the modeling trends (Fig. 3) which accounts for the large age uncertainty reported here and suggests other processes have affected this FAN. The radiometric age dating of 67215 needs to be revisited.

Conclusions: We present a method to age date FANs on the assumption that Sm-Nd ages represent

crystallization from the LMO. It opens up the possibility for age dating FANs that are not appropriate for isochron determinations. More on this can be found in [28]. However, only data from the cores of the largest relict plagioclases should be used in this endeavor (Fig. 2). Smaller crystals that have experienced cataclasis and recrystallization may give spurious results.

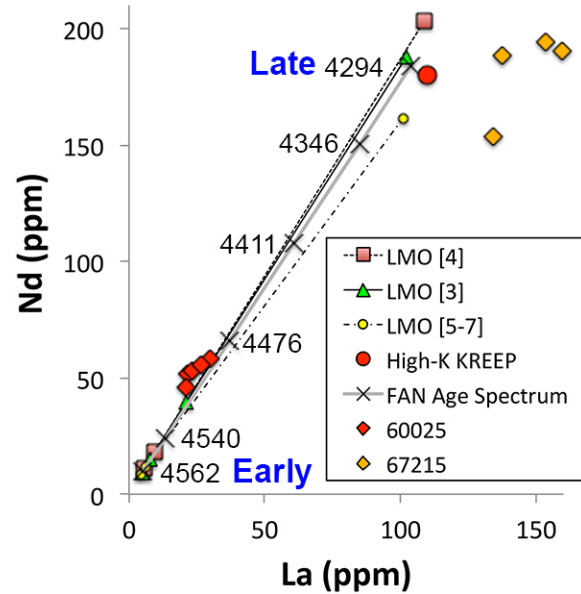


Figure 3: Model paths for the last stages of LMO evolution (when plagioclase is crystallizing) with the FAN age spectrum. Early and Late stage FANs are indicated. Numbers = age (Ma) calibrated by modeling results.

References: [1] Dowty E. et al. (1974) *EPSL* 24, 15-25.

- [2] Taylor S. & Jakes P. (1974) *PLSC* 5, 1287-1305. [3] Snyder G. et al. (1992) *GCA* 56, 3809-3823. [4] Elkins-Tanton L. et al. (2011) *EPSL* 304, 326-336. [5] Rapp J. & Draper D. (2012) *LPSC* 43, #2048. [6] Rapp J. & Draper D. (2013) *LPSC* 44, #2732. [7] Rapp J. & Draper D. (2014) *LPSC* 45, #1527. [8] Borg L.E. et al. (2011) *Nature* 477, 70-72. [9] Gaffney A. & Borg L. (2014) *GCA* 140, 227-240. [10] Borg L. et al. (2015) *MaPS* 50, 715-732. [11] Neal C.R. & Draper D. (2016) *LPSC* 47, #1165. [12] Snyder G. et al. (1994) *LPSC XXV*, 1309-1310. [13] Marks N. et al. (2014) *LPSC* 45, #1129. [14] Carlson R. & Lugmair G. (1988) *EPSL* 90, 119-130. [15] Borg L. et al. (1999) *GCA* 63, 2679-2691. [16] Alibert C. et al. (1994) *GCA* 58, 2921-2926. [17] Nyquist L. et al. (2010) *LPSC* 41, #1383. [18] Norman M. et al. (2003) *MaPS* 38, 645-661. [19] Nyquist L. et al. (2006) *GCA* 70, 5990-6015. [20] Papike J. et al. (1998) *Rev. Min.* 36, 5-1 – 5-234. [21] Carlson R. et al. (2014) *Phil. Trans. Roy. Soc. A* 372, 20130246. [22] Shearer C. et al. (2013) *LPSC* 44, #1689. [23] James O. et al. (1991) *PLPSC* 21, 63-87. [24] McCallum I. et al. (1975) *EPSL* 25, 36-53. [25] Yamaguchi A. et al. (2010) *GCA* 74, 4507-4530. [26] Papike J. et al. (1997) *GCA* 61, 2343-2350. [27] Floss C. et al. (1998) *GCA* 62, 1255-1283. [28] Torcivia M. et al. (2017) *LPSC* 48.